Preprint
UCRL-JC-147441

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This article was submitted to 3rd Symposium on Current Trends in International Fusion Research, Washington, DC March 8-12, 1999

February 19, 2002

U.S. Department of Energy

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PROGRESS AT LLNL TOWARD DPSSL-DRIVEN INERTIAL FUSION ENERGY

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ABSTRACT

We describe research indicating that a diode-pumped solid-state laser (DPSSL) can serve as a viable driver for an inertial fusion energy (IFE) power plant. The ongoing construction of the National Ignition Facility (NIF) sets the stage for a new era to start in the next decade for target research aimed at achieving the high gains necessary for both defense and energy applications. In addition, advances in DPSSL research show that this type of laser can have adequate efficiency and reliability, and can achieve the effective beam smoothness required for direct-drive IFE.

1. INTRODUCTION

Interest in laser-driven inertial fusion energy (IFE) continues to grow because of the construction of the National Ignition Facility (NIF) and the progress achieved in diode-pumped solid-state laser (DPSSL) [1–6] and KrF laser [7–12] research. The progress in DPSSL research indicates that a DPSSL can serve as a viable driver for IFE. In this paper, we concentrate on the advances made at the Lawrence Livermore National Laboratory (LLNL) relating to the construction of the 100-J Mercury laser, and new results that reveal how a DPSSL can achieve a suitable beam smoothness for direct-drive IFE.

2. THE NIF

The NIF will be a pivotal facility for IFE research because of its mission to demonstrate ignition and propagating burn in the laboratory. This mission will be accomplished by using a 192-beam flashlamp-pumped Nd:glass laser to irradiate targets at 1.8 MJ and 500 TW in temporally and spatially tailored 351-nm pulses. The NIF's most significant accomplishment relating to IFE is expected to be the determination of the ignition threshold for each major type of target, and hence the operating point for IFE. The ignition threshold will determine the driver size, and hence its cost. Next in importance for IFE should be the insight relevant for the design of an IFE target with a gain on the order of 100 or more. Such energy gains are important to reduce the cost of electricity for a given laser cost. Research on the NIF is also expected to provide the needed understanding for such things as the precise requirements for shaping each laser pulse in time, how spatially smooth each focused laser beam must be (e.g., the required bandwidth for smoothing), and complete understanding of the relevant plasma instabilities inherent in the coupling of laser energy into an indirect-drive hohlraum and the generation of x rays to implode a capsule in a stable manner. Construction of the NIF is now well under way, and the first beam bundle of 8 laser beams (equivalent to two Nova lasers) will be operational in 2001. Completion of the full 24 bundle system is planned for October 2003, with a demonstration of capsule energy gains of 1 to 10 before the year 2008.

3. DPSSL RESEARCH

Flashlamp-pumped Nd-glass lasers like the NIF have an overall efficiency of about 0.5% and are inherently “single-shot” machines, requiring several hours to recover from thermally induced optical distortions in the gain media. In contrast, an IFE driver must satisfy more demanding criteria:

- Efficiency of >5%.
- Rep-rate of ~10 Hz.
- Reliability of $>10^9$ shots ($2x10^4$ are planned for the NIF).
- Beam smoothness of <1% averaged over 0.2–1 ns for direct drive (low ℓ-modes).
- Cost of < $1.5B for 1 GWe.

Both DPSSLs and KrF lasers are considered to meet these criteria.

The DPSSL approach is directly related to flashlamp-pumped Nd:glass solid-state lasers with regard to pumping, energy storage, extraction, multi-pass amplifier architecture, light propagation, linear and nonlinear wavefront distortions, frequency conversion, temporal pulse shaping, and beam smoothing. The DPSSL approach therefore builds on the last two decades of solid-state laser and target development. In particular, DPSSLs represent an extension of solid-state laser technology toward IFE because they can employ the following:

- Narrow-frequency-band laser-diode arrays instead of wide-frequency-band flashlamps to pump the gain media, therefore offering higher pump efficiency with less heat deposition.
- Yb:crystal gain media [2] instead of Nd:glass, therefore offering four times the thermal conductivity, thus permitting near-sonic helium cooling [3] of the gain media for rep-rated operation without stress fracture.

The Yb:crystal gain media also provide an energy storage lifetime of 1.1 ms, which is three times larger than that for Nd:glass; the longer storage lifetime reduces the cost required for the laser diodes. Therefore, if the price of diodes decreases in response to a growing market size, a DPSSL driver may turn out to be practical for IFE because a DPSSL appears as though it might be able to (1) scale to MJ output energies on target and (2) achieve an affordable development path because of its modularity. To this end, a number of DPSSL facilities have been envisioned at LLNL to integrate the approaches and develop new capabilities for irradiating inertial-fusion targets. These begin with the Mercury Laser having 100 J at 10 Hz, then an Integrated Research Experiment (IRE) laser driver delivering a few kJ, leading eventually to a MJ-class power-plant driver. This DPSSL development track could proceed in parallel with NIF target research.

Note that the modularity of a DPSSL means that its functionality can be validated at the component level or at the single-beam level, thus permitting experimental verification at reduced development cost. In addition, many of the novel laser-diode technologies envisioned for an IFE driver are relevant to a variety of scientific, industrial, and military applications and will therefore continue to advance in parallel with inertial confinement fusion (ICF) developmental efforts.

One area of particular importance for direct drive is the achievement of adequate beam smoothness on target. Specifically, sufficient laser bandwidth (≥1 THz) is required to avoid implanting perturbations during the early stages of capsule implosion that can lead to significant hydrodynamic instability growth. Our calculations now show that a DPSSL can achieve this required beam smoothness. In particular, DPSSLs have the modularity to permit separate generation of the initial “foot” and following “main” portions of a capsule temporal drive pulse. These portions of the temporal pulse can be subsequently combined using a total solid angle at the fusion chamber of order 5% or less. The foot pulse could comprise 10 to 15% of the energy using Nd:glass amplifiers and multi-crystal triplers to produce as much as 3 THz of bandwidth. Even though the tripler might be operated at reduced efficiency, the consequence to the overall efficiency would be mitigated because the foot pulse contains only a small fraction of the total pulse energy. Such a laser configuration for the foot pulse would minimize seeding of Rayleigh-Taylor instabilities in the initial implosion. The main pulse could be an assemblage of beamlets operating at slightly different wavelengths, using the four gain peaks (i.e., four colors) available from the ytterbium-doped fluorapatite gain media [based on M = Sr, Ca, and Ba in the chemical formula Yb^{3+}:$M_5(PO_4)_3F$]. Each of these gain peaks is known to have ~0.3 THz bandwidth, so the assemblage of beamlets can have sufficient beam smoothing for the main peak (and ~80% conversion to UV). In addition, relative to the foot pulse, the main-pulse beams could offer a smaller spot size to accommodate the reduced size of the imploding target. Such an approach provides a net beam smoothness that exceeds what the NIF can achieve for a bandwidth of 1 THz.[13]

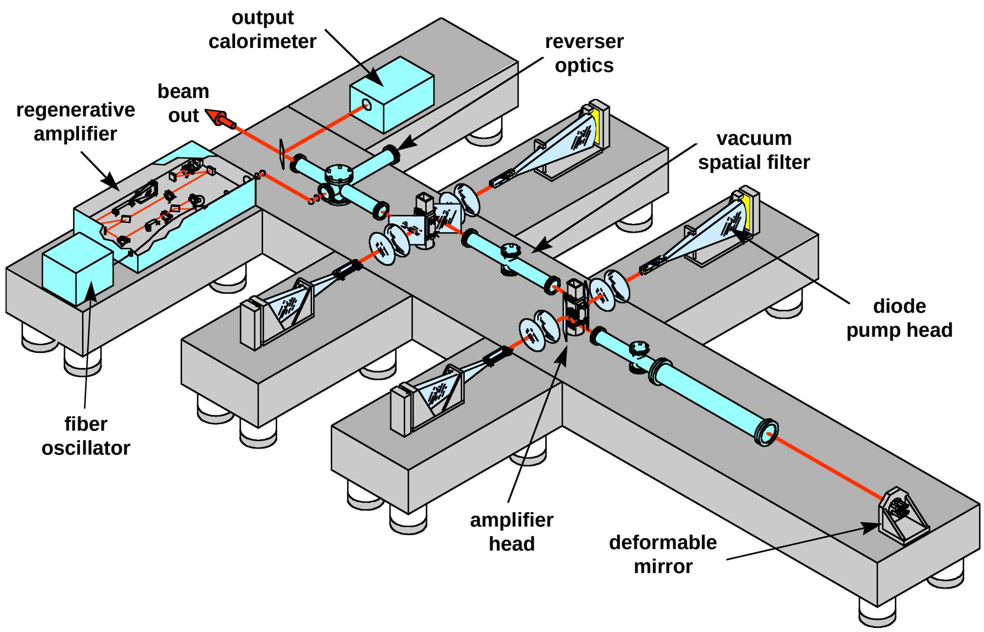

Fig. 1 Table layout of the Mercury baseline architecture.

4. MERCURY LASER

The goals of the Mercury Project [6] are to produce a DPSSL delivering 100 J with an overall electrical efficiency of ≥10% at the first harmonic, a final focus less than 5 times the size for a diffraction-limited beam, pulse lengths of 2 to 10 ns, and a repetition rate of 10 Hz. Although small in scale, the Mercury laser will demonstrate the utility of a DPSSL as an IFE power plant driver in terms of pulse duration, laser efficiency, and thermal management, but not in total energy output (although the energy output will be more than an order of magnitude larger than any other pulsed diode-pumped laser ever built). Subsequent research must demonstrate efficient average-power frequency conversion and beam smoothing, and temporal pulse shaping that permits an overall efficiency of 10%. Propagation calculations for Mercury in 1D and 2D using our PROP92 computer code [14] are helping us optimize the Mercury system, and several advanced architectures are being considered for the final design. Meanwhile, fabrication of key components (thermal-management systems, laser-diode pump arrays, and crystals) have already begun.

Specifically, the baseline architecture for Mercury (Fig. 1) consists of a four-pass cavity with angular multiplexing and a reverser section to reverse the beam direction between passes two and three. Each of the two amplifier heads contains seven Yb:S-FAP [Yb^{3+}-doped $Sr_5(PO_4)_3F$] crystals each 0.75 cm thick.[2] Each amplifier head is pumped along the laser beam direction by two arrays of 900-nm laser diodes, one array with its homogenizer tube and telescope optics on each side of the amplifier head. During a 1-ms pump pulse, each laser diode array exhibits thermal sag <10% and acceptable thermal chirp (linewidth <5 nm FWHM).[15]

One amplifier should be operational this year, possibly with surrogate crystals to facilitate examination of crystal mounting techniques and thermal issues. Growth of the Yb:S-FAP crystals at the appropriate size for the 3 x 5 cm^2 active beam area is progressing, and production runs should begin within two months. Crystals of nearly adequate quality and roughly half the required size have already been grown, and techniques to bond two crystals together to make a full-size crystal have been demonstrated. Modification of the baseline design to achieve lower optical damage threats to the final transport optics and scalability to the kilojoule beam size are under consideration. The gas-cooling system and power conditioning are currently in place.

5. FURTHER DEVELOPMENT

A laser driver for IFE must be affordable and environmentally acceptable as well as technically viable. The direct affordability of a DPSSL driver depends primarily on the price of the laser diodes, and DPSSL-driven IFE will be practical only if the expected price reductions occur as volume production in a fusion economy begins. In addition, the final optics must be protected from x-ray and neutron bombardment to enable the long life required for minimal maintenance. Low-dose experimental exposures of fused-silica materials support the idea that DPSSL final optics can be operated at 400 °C to continuously anneal defects from neutron interactions for $\lambda \geq \sim 350$ nm, but high-dose experimental verification is lacking.

A laser driver must also have a viable fusion-chamber concept, whose development must consider the effect of first-wall protection on the required target gain and the desired plant availability factor (≥80%). Other chamber issues that must be resolved concern target injection (and the associated beam-alignment tolerances) and pulsed-neutron damage to materials. There must also be more study to optimize the efficiency of frequency conversion in the presence of beam bandwidths ≥1 THz.

6. CONCLUSIONS

Interest in a DPSSL as an IFE driver is growing. The NIF is now under construction and is expected to achieve fusion gains of 10 to 20 in the laboratory. Not only should the NIF determine the minimum threshold for target ignition for IFE, but it should resolve remaining issues concerned with target physics. The Mercury Laser is also under construction at LLNL, and should begin first-stage operation later this year. This will be the first laser to demonstrate 10-Hz operation at an output energy of 100 J with 10% efficiency using a scalable laser architecture. In addition, we calculate a beam smoothness for DPSSL IFE that exceeds what the NIF can achieve for a bandwidth of 1 THz.[13] It would therefore appear that DPSSLs are indeed a viable candidate for an IFE driver.

ACKNOWLEDGMENTS

We wish thank our many colleagues for their contributions, including our Mercury colleagues A. Bayramian and J. Lawson for analyzing the Yb:S-FAP crystals, R. Beach and C. Bibeau for developing the baseline architecture, C. Ebbers for frequency-conversion activities, M. Emanuel and J. Skidmore for developing the laser diode arrays, B. Krupke for his early conceptualization of the laser system, C. Marshall for initiating and defining the project, K. Schaffers for growing the crystals, and S. Sutton for developing the gas-cooled slab approach. The research reported here was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract number W-7405-Eng-48.

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